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Trends of solar radiation, cloudiness and atmospheric transparency during recent decades in Estonia

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ABSTRACT

Data obtained during 1955–1986 at the Tôravere Actinometric Station (Estonia, USSR) are used to study the long-term variations of the direct (S') and global solar radiation (Q) at the earth's surface. During these years, a certain decreasing trend was observed both in S' and in Q ($\Delta S' = -13\%$, $\Delta Q = -6.8\%$). The results from Tôravere are compared with the data on global radiation acquired in 1964–1986 at 9 different actinometric stations in northern Europe (8) and western Siberia (1). Decreasing trends have been observed in Helsinki and Stockholm ($\Delta Q = -11\%$), and also in Kaunas ($\Delta Q = -12\%$) in the same period. The variations of the cloudiness regime and atmospheric transparency as the main reasons for the decrease of radiation are discussed. According to the measurement data from Tôravere, the mean annual amount of low clouds increased by 11%, whereas the value of the Bouguer atmospheric transparency coefficient decreased by 3.7%.

1. Variations of direct and global solar radiation

The measurements of solar radiation at the Tôravere Actinometric Station, Estonian SSR ($\varphi = 58°16'$N, $\lambda = 26°28'$E), have been carried out for more than 30 years. As receivers of solar radiation, the following devices were used: for direct solar radiation, the Yanishevsky thermoelectric actinometer; for diffuse radiation, the Yanishevsky thermoelectric pyranometer. The global radiation has been calculated as the total of direct and diffuse radiation incident on a horizontal surface. All actinometric instruments were calibrated once a month against the etalon actinometer, whose sensitivity has remained unchanged for the last 30 years. The actinometric scale carrier at Tôravere is the Ångström pyrheliometer, calibrated against the Soviet subetalon once in 2–3 years. The calibration system of this kind permits avoidance systematic errors in the actinometric data. Thus, comparison of the observational data from different years allows the long-term variations of radiation balance components to be examined.

The analysis of annual means of the daily totals of the global (Q) and direct radiation (S') incident on a horizontal surface during 1955–1986 revealed that, besides usual dispersion, there is a certain decreasing tendency in temporal course (Fig. 1). The radiation data are given in the new pyrheliometric scale, the World Radiometric Reference (WRR), recommended by WMO in 1981 (Kmito et al., 1983). In order to estimate the statistical significance of the linear trend, the time series of the mean daily totals was approximated to the straight line $Q = a + bx_i$ (the straight line parameters a and b were derived by the method of least squares, x_i denotes the number of the year of observation). Next, the value of the Student parameter t was produced from the equation

$$t = b\sqrt{\frac{\sum_{i=1}^{N}(x_i - \bar{x})^2}{\frac{1}{N-2}\sum_{i=1}^{N}[Q_i - (a + bx_i)]^2}},$$

where N is the total number of the years of observation.

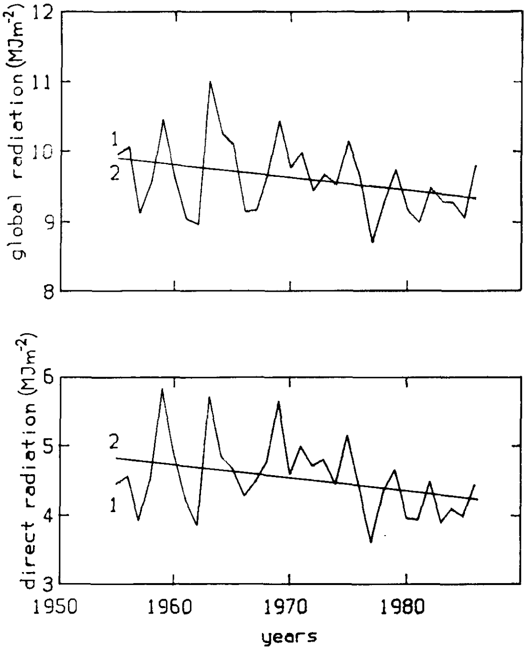

Fig. 1. The time series (1) and linear approximation (2) of the daily totals of global and direct solar radiation averaged over a year.

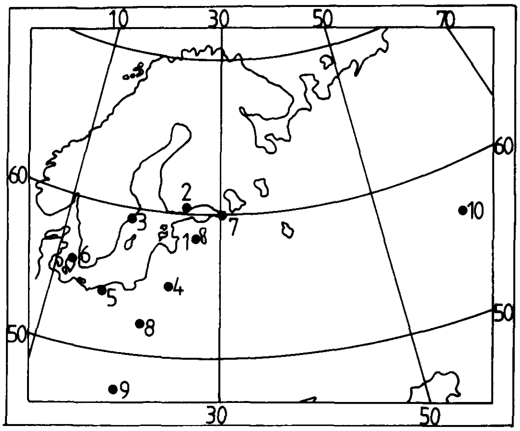

Fig. 2. Schematic map of the locations of actinometric stations. 1, Tôravere; 2, Helsinki; 3, Stockholm; 4, Kaunas; 5, Kolobrzeg; 6, Taastrup; 7, Leningrad; 8, Warsaw; 9, Budapest; 10, Sverdlovsk.

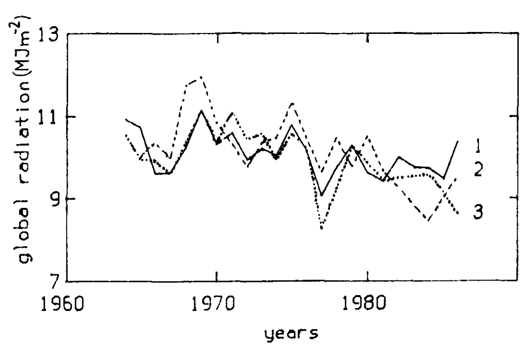

Fig. 3. The temporal courses of the daily totals of global radiation obtained at the actinometric stations of Tôravere, Helsinki and Stockholm. The data missing in the original source are derived by linear interpolation. 1, Tôravere; 2, Stockholm; 3, Helsinki.

Our results confirmed the presence of the linear trend: the significance levels (p) for the global and direct solar radiation exceeded 0.97 and 0.95, respectively. According to the linear trend, the annual means of the daily totals of the direct and global radiation incident on a horizontal surface during 32 years of observations had decreased by 13.0% and 6.8%. However, we could not determine a reliable trend for the temporal course of diffuse radiation.

In addition to the radiation data from Tôravere, we also analyzed the data on the annual means of daily totals of global radiation in 1964–1986 received from 9 different actinometric stations (Helsinki, Stockholm, Taastrup, Warsaw, Kolobrzeg, Budapest, Kaunas, Leningrad and Sverdlovsk, Fig. 2) and published by the A. I. Voeikov Main Geophysical Observatory (Solar Radiation and Radiation Balance Data, The World Network). The temporal courses of radiation in this period obtained at the actinometric stations at Tôravere, Kaunas (1964–1985), Helsinki and Stockholm (data of 1964 are missing) were similar (Fig. 3). At the Kaunas actinometric station, $\Delta Q = -12.5\%$; in Helsinki $\Delta Q = -11.4\%$; in Stockholm $\Delta Q = -11.5\%$. The linear trends for other actinometric stations were found to be much weaker.

Fig. 3 is an illustration of a more rapid decrease of radiation since 1969 observed at the actinometric stations of Tôravere, Helsinki and Stockholm. Therefore, an additional analysis of the radiation data acquired from 1969 to 1986 at 10 actinometric stations was also carried out. The analysis showed that the significance level for the decrease of global solar radiation at the stations of Tôravere, Helsinki and Stockholm had arisen:

$p \geqslant 0.99$. At the same time, a significant decrease of radiation was observed at the Leningrad, Kolobrzeg and Taastrup actinometric stations ($p \geqslant 0.95$). During 18 years of observations, the global radiation in Taastrup, Kolobrzeg and Leningrad had decreased on the average by 11.6%, 7.7% and 6.4%, respectively.

2. Cloudiness variations

Cloudiness conditions are treated as the most significant regulator of the radiation regime at Tôravere (actual annual mean sunshine duration accounts only for 36% of the possible duration on cloudless days here). Thus, the decrease of radiation is most probably due to cloudiness variations. A statistically significant decrease of radiation has been observed at the actinometric stations located near the Baltic Sea. The weather in these regions is mainly determined by the cyclones moving eastwards from the Atlantic Ocean. We assume that a certain change has taken place in the atmospheric circulation of the area. For the actinometric stations situated further from the Baltic Sea (Budapest, Sverdlovsk), we could not yet identify a distinct decreasing trend of global radiation. In these regions, the cloudiness regime is less influenced by the Atlantic cyclones. In Sverdlovsk, situated in deep inland, the global radiation has in contrast increased during the period 1969–86 (Table 1).

Table 1. *Significance levels (p) for linear trends*

Stations	p	ΔQ	p	ΔQ
	1964–86		1969–86	
Tôravere	0.98	−7.3	0.99	−8.4
Helsinki	0.98	−11.4	0.99	−16.0
Stockholm (1965–86)	0.95	−11.5	0.99	−14.8
Kaunas (1964–85)	0.99	−12.5	0.98	−13.2
Kolobrzeg	0.60		0.95	−7.7
Taastrup	0.70		0.95	−11.6
Leningrad	0.30		0.95	−6.4
Warsaw	0.90	−5.2	0.80	
Budapest	0.30		0.60	
Sverdlovsk	0.40		0.90	+5.2

Changes in the annual means of the daily totals of global radiation (ΔQ in %). The values of ΔQ are given only for the trends having $p \geqslant 0.9$.

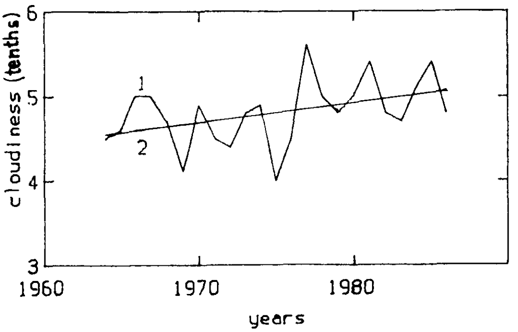

Fig. 4. Time series (1) and linear approximation (2) of the mean annual amount of low clouds at Tôravere.

In order to determine the influence of cloudiness variations on the decrease of radiation, we used the data from visual cloudiness observations (type and amount of high, middle and low clouds) received with a 1-h interval in daylight hours at Tôravere. We derived the mean annual amount both of the low and the total clouds n using the following equation

$$n = \frac{\sum_{i=1}^{12} n_i Q_i^0}{\sum_{i=1}^{12} Q_i^0},$$

where n_i is the mean amount of low or total clouds, respectively, in single months and Q_i^0 is the possible monthly total of global radiation under a cloudless sky. The equation also allows us to consider the effect of cloudiness of each single month on the decrease of the mean annual radiation.

The analysis of the cloudiness time series revealed that the cloudiness conditions at Tôravere have undergone significant changes during recent decades. In Fig. 4, we can see that during 1964–1986, the mean annual amount of low clouds increased by 11%. However, we could not find a reliable trend for the temporal course of total cloudiness.

The total radiation incident on a horizontal surface from April to September at Tôravere makes up 82% of the annual total value. Therefore, considering the effect of cloudiness on the radiation regime of the region, we confined ourselves to the data of the above-mentioned

Table 2. *Significance levels* (p) *for linear trends and increase of the mean monthly and annual amounts of cloudiness at Tôravere* (Δn *in units of* 0.1) *during 1964–86*

Months	p	Δn
	low cloudiness	
April	0.20	
May	0.40	
June	0.98	1.4
July	0.90	1.1
August	0.50	
September	0.95	1.5
annual	0.95	0.5
	total cloudiness	
annual	0.80	

The values of Δn are given only for the trends having $p \geqslant 0.9$.

months, only. The same techniques were used to determine the changes of the amount of low clouds within single months. We observed a reliable increase of cloudiness in June and in September (Table 2). The increase of cloudiness in July is questionable, however, since the significance level of the trend is merely 0.9.

3. Variations of atmospheric transparency

Besides the increase of cloudiness, we must also consider the long-term changes of atmospheric transparency as a possible cause for radiation regime variations. As a characteristic of atmospheric transparency, the Bouguer atmospheric transparency coefficient P_2 at the air mass $m = 2$ was derived from the following equation

$$P_2 = \sqrt{S_2/S_0},$$

where S_2 is the intensity of direct solar radiation reduced to the Earth–Sun mean distance and to $m = 2$ by the method presented by Mürk (1959). The solar constant $S_0 = 1.367$ kW m^{-2}. The temporal course of the annual means of P_2 at Tôravere shows a continuous increase of atmospheric turbidity (Fig. 5) (Russak, 1987). In addition to the relatively short-term variations of atmospheric turbidity which may be treated as due to the influence of volcanic eruptions, we have also identified a linear trend and a decrease

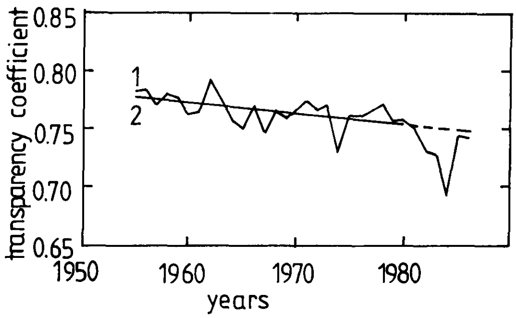

Fig. 5. The long-term time course (1) and linear approximation (2) of the mean annual Bouguer transparency coefficient reduced to the atmospheric air mass $m = 2$.

of P_2 by 3.7% ($p \geqslant 0.97$) in the course of 32 years. Due to the considerable influence of volcanic activity on the optical parameters of the atmosphere in 1981–1984, we neglected the data of these years in the trend calculations (as a result of successive volcanic eruptions, the self-cleaning ability of the atmosphere had dropped, which led to the accumulation of volcanic products in the atmosphere (Rusina and Rodionov, 1984)).

The decrease of atmospheric transparency within single months is different. The greatest decrease of atmospheric transparency has been obesrved in April ($P_2 = -7.6\%$, 0.99), in May (-4.1%, 0.92) and in June (-5.8%, 0.98). In other months, the decrease has either been smaller or statistically less reliable. A rapid decrease of the monthly mean transparency has been observed at Tôravere from March to April (Russak, 1987). Similar results have been obtained by the Arctic haze investigations in Canada (McGuffic et al., 1985), where the maximum of the aerosol optical depth was observed in April–May. The Arctic haze effect is probably caused by the content of anthropogenic sulfates. Thus, the increasing atmospheric turbidity in spring might be explained by the significant content of man-made pollutants at Tôravere by that time. One possible factor contributing to the seasonal variation of the P_2 trend may be the decreased cleaning effect of precipitation in spring. Sunshine, too, favours the photochemical processes in the atmosphere, which lead to the generation of relatively stable chemical compounds from man-made pollutants. Under favourable atmospheric circulation, these chemical compounds may be carried far away from the place of their generation (at Tôravere and its nearest surroundings, such sources of anthropogenic pollution are missing). The comparison of the turbidity data with the aerosol data could not be provided, as such measurements are lacking in Estonia.

The significant increase of atmospheric turbidity observed during the three past decades marks an increase of the amount of the matter capable of absorption and scattering of radiation. Radiation absorption, however, may lead to variations in the energy balance of the atmosphere. These in their turn determine the weather processes in the atmosphere and may lead to variations in atmospheric circulation. At the same time, we must treat the growth of the amount of atmospheric aerosols as an increase in the amount of possible condensation nuclei.

One cannot tell whether the variations of solar radiation, cloudiness and atmospheric transparency discussed in the present paper are going to continue for some time or whether it is only a phase in the long-term variations of meteorological parameters. Thus, in some time, these variations may progress in the opposite direction. However, the problem of the influence of anthropogenic pollution on atmospheric circulation remains open.

4. Acknowledgements

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